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Author

Simmons, Elizabeth H

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Limitations of B-meson mixing bounds on technicolor theories

Elizabeth H. Simmons*

Department of Physics, Boston University,
590 Commonwealth Ave., Boston MA 02215

Physics Department, Harvard University, Cambridge MA, 02138

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Abstract

Recent work by Burdman, Lane, and Rador has shown that $B\bar{B}$ mixing places stringent lower bounds on the masses of topgluons and Z' bosons in classic topcolor-assisted technicolor (TC2) models. This paper finds analogous limits on the Z' bosons of flavor-universal TC2 and non-commuting extended technicolor models, and compares the limits with those from precision electroweak measurements. A discussion of the flavor structure of these models (contrasted with that of classic TC2) shows that B-meson mixing is a less reliable probe of these models than of classic TC2.

*e-mail address: simmons@bu.edu

The flavor problem remains a challenge for dynamical models of mass generation. While technicolor [1] can provide appropriate masses for the electroweak gauge bosons, explaining the masses and mixings of the quarks and leptons is more difficult. Extended technicolor models [2] postulate an enlarged gauge group coupling the quarks and leptons to the technifermion condensate, enabling them to acquire mass. However, the simplest models of this type tend to produce large flavor-changing neutral currents. Given the large value of the top quark's mass and the sizable splitting between the masses of the top and bottom quarks, it is natural to wonder whether m_t has a different origin than the masses of the other quarks and leptons. A variety of dynamical models that exploit this idea have been proposed, including topcolor-assisted technicolor (TC2)[3], flavor-universal TC2 [4], and non-commuting extended technicolor (NCETC) [5].

A common feature of these models is that they extend one or more of the standard model $SU(N)$ gauge groups to an $SU(N) \times SU(N)$ structure at energies well above the weak scale. The TC2 models have extended color and hypercharge groups; NCETC has an extended weak gauge group. Spontaneous breaking of the extended groups to their diagonal (standard model) subgroups produces extra massive gauge bosons: a color-octet of topgluons plus a Z' boson in TC2, a color-octet of colorons and a Z' boson in flavor-universal TC2, and a trio of W' and Z' bosons in NCETC. In order to use their enlarged gauge groups to help explain the heavy top quark mass, all of these models propose that some of the gauge groups should be flavor non-universal, treating the third generation fermions differently than those in the first and second generations. Accordingly, the topgluons and Z' of classic TC2, the Z' of flavor-universal TC2, and the extra weak bosons of NCETC all have flavor non-universal couplings – meaning that these gauge bosons can cause tree-level flavor-changing neutral currents.

Recently, Burdman et al. [6] pointed out that $B_d\bar{B}_d$ mixing provides strong lower bounds on the masses of the topgluon and Z' bosons of classic TC2 models. They briefly mentioned that their work should constrain flavor-universal TC2 models, but did not present specific results for those models. This paper explicitly extends the analysis to study both flavor-universal TC2 and non-commuting ETC. We find that the limits on the gauge bosons of these models are numerically much weaker than those for classic TC2 models and are comparable to limits from precision electroweak observables. In addition, we show that the flavor structure of these models differs from that of classic TC2 in ways that render limits from B-meson mixing less generally applicable.

Exchange of a heavy gauge boson G with non-universal couplings of the type discussed above gives rise to the following $|\Delta B| = 2$ interaction at low energies:

$$\mathcal{H}_G = \frac{2\pi\alpha_G}{M_G^2} \sum_{\lambda_1, \lambda_2=L,R} \left(D_{\lambda_1 bb}^* D_{\lambda_1 bd_i} [A_{G\lambda_1}^b - A_{G\lambda_1}^d] (\bar{b}_{\lambda_1} \gamma^\mu \Gamma^G d_{\lambda_1}) \right) \times \\ \left(D_{\lambda_2 bb}^* D_{\lambda_2 bd_i} [A_{G\lambda_2}^b - A_{G\lambda_2}^d] (\bar{b}_{\lambda_2} \gamma^\mu \Gamma^G d_{\lambda_2}) \right) + h.c. \quad (1)$$

The mass of the gauge boson is M_G and the fine structure constant of the relevant Standard Model gauge group is α_G . The matrix Γ^G is $\lambda^a/2 [T^a, 1]$ if G comes from an extended SU(3) [SU(2), U(1)] gauge group. The factor $A^b G \lambda_i$ ($A^d G \lambda_i$) is the full strength (modulo the gauge coupling $\sqrt{4\pi\alpha_G}$) with which boson G couples to a λ_i -handed b (d or s) quark through the $SU(N)_1$ and $SU(N)_2$ bosons and any bosons that mix with them. The matrices D_{λ_i} represent the mixing between λ_i -handed down-type quarks. Equation (1) is a slight generalization of equations (5) and (6) of ref. [6]; the additional terms included here are numerically irrelevant for the results of Burdman et al., but will be needed in our analysis.

As discussed in ref. [6], the primary effect of the topgluon from classic TC2 on B-meson mixing comes from its exchange among left-handed gauge-eigenstate b -quarks. Since b is an $SU(3)_1$ triplet and an $SU(3)_2$ singlet, while d (and s) is just the opposite, one finds $A_{CL}^b = \cot \theta_C$ and $A_{CL}^d = -\tan \theta_C$ in eq. (1). The main contribution from the Z' comes from the $U(1)_{1,2}$ charges ($Y_{1,2}$) of the left-handed down-type quarks; e.g., $A_{YL}^b = Y_{1L}^b \cot \theta_Y - Y_{2L}^b \tan \theta_Y$. The combined contribution to the $B_L^0 B_S^0$ mass difference is given [7] by $\Delta M_{B_d} = 2|M_{12}|_{TC2}$

$$2(M_{12})_{TC2} = \frac{4\pi}{3} \eta_B M_{B_d} f_{B_d}^2 B_{B_d} (D_{Lbb}^* D_{Lbd})^2 \mathcal{R}_{TC2} \quad (2)$$

$$\mathcal{R}_{TC2} = \left[\frac{\alpha_C \cot^2 \theta_C (1 + \tan^2 \theta_C)^2}{3M_C^2} + \frac{\alpha_Y \cot^2 \theta_Y ((Y_{1L}^b - Y_{1L}^d) - (Y_{2L}^b - Y_{2L}^d) \tan^2 \theta_Y)^2}{M_{Z'}^2} \right] \quad (3)$$

where the dependence on gauge boson couplings and masses has been collected in the expression \mathcal{R} for later convenience. In the above equations, α_C (α_Y) is the Standard Model fine structure constant for color (hypercharge), M_C ($M_{Z'}$) is the topgluon (Z') mass, and θ_C (θ_Y) is the mixing angle between the two original color (hypercharge) groups. Following ref. [6], we set the QCD radiative correction factor for the LL product of color-singlet currents to $\eta_B = 0.55 \pm 0.01$ and use $f_{B_d} \sqrt{B_{B_d}} = (200 \pm 40)$ MeV [7] to incorporate the B_d meson decay constant and bag parameter.

Ref. [6] argues that, in classic TC2 models, quark mixing occurs almost exclusively in the left-handed down-quark sector of those models and, in consequence, the factor $D_{Lbb}^* D_{Lbd}$ appearing in the expression for $(M_{12})_{TC2}$ is approximately equal to $V_{tb}^* V_{td}$. This means that the quark mixing factor appearing in $(M_{12})_{TC2}$ is identical to that in the standard one-loop contribution from W exchange (which is also present in ETC and TC2 models). The two contributions to neutral B-meson mixing therefore add constructively. We will refer to this situation as the “constructive” scenario. To facilitate a comparison of the limits obtained for different models, we will start by assuming that the constructive scenario also applies in

the models we are considering. Then, we will examine quark mixing in the flavor-universal TC2 and NCETC models in more generality and discuss the implications.

We can find limits on the Z' bosons of the flavor-universal TC2 and NCETC models by scaling from the results of ref. [6] based on the \mathcal{R} factors for the different models. To begin, we reproduce the value of \mathcal{R}_{TC2} obtained in ref. [6]. On the RHS of eq. (3), the first term dominates, due to the large topgluon gauge coupling and the anticipated similar sizes of the topgluon and Z' masses. Following ref. [6], we approximate \mathcal{R}_{TC2} by its first term, setting $\cot^2 \theta_C \approx 25$ and $\alpha_C(1 \text{ TeV}) = 0.093$, and obtain

$$\mathcal{R}_{TC2} \approx \frac{\alpha_C \cot^2 \theta_C}{3M_C^2} \approx \frac{0.8}{M_C^2}. \quad (4)$$

Ref. [6] showed that applying the experimental limit $\Delta M_{B_d} = (3.11 \pm 0.11) \times 10^{-13} \text{ GeV}$ [8] to eq. (2) yields a lower bound on the topgluon mass. The value of the bound is $M_C \gtrsim 3.1 \text{ TeV}$ if ETC contributes significantly to the Kaon CP-violation parameter ϵ and $M_C \gtrsim 4.8 \text{ TeV}$ if it does not.

In the flavor-universal TC2 model [4], the gauge group is the same as in classic TC2 [3]: $G_{ETC} \times SU(3)_1 \times SU(3)_2 \times SU(2) \times U(1)_1 \times U(1)_2$. The fermion charge assignments are different than in classic TC2: here, all quarks are $SU(3)_1$ triplets and $SU(3)_2$ singlets. The color-octet of coloron bosons in the low-energy spectrum therefore couples with equal strength ($A_C^b = A_C^d = \cot \theta_C$) to all quarks and does not generate flavor-changing neutral currents (unlike the topgluons of classic TC2). The factor \mathcal{R} does not have a coloron contribution, only a contribution from the non-universal Z' bosons (third-generation fermions feel $U(1)_1$ and the others feel $U(1)_2$):

$$\mathcal{R}_{univ-TC2} = \left[\frac{\alpha_Y \cot^2 \theta_Y (Y_{1L}^b + Y_{2L}^d \tan^2 \theta_Y)^2}{M_{Z'}^2} \right] \quad (5)$$

As discussed in ref. [4], self-consistency in the treatment of the more strongly-coupled $U(1)_1$ group (i.e., avoiding the Landau pole) requires $\alpha_Y \cot^2 \theta_Y \equiv \kappa_1 \lesssim 1$. The benchmark flavor-universal model has standard-model values for the fermion hypercharges, so that $Y_{1L}^b + Y_{2L}^d \tan^2 \theta_Y)^2 \approx 1/36$ (for small $\tan^2 \theta_Y$). Then

$$\mathcal{R}_{univ-TC2} \approx \frac{0.028}{M_{Z'}^2}. \quad (6)$$

The lower limit on $M_{Z'}$ of flavor-universal TC2 is roughly a factor of 5 weaker than that on the topgluons of classic TC2. Scaling from the results of ref. [6], we find $M_{Z'} \gtrsim 590 \text{ GeV}$ if ETC does contribute to ϵ and $M_{Z'} \gtrsim 910 \text{ GeV}$ if it does not. This is comparable to the previous lower bounds on the Z' mass from precision electroweak fits [9], which range from 500 GeV to over 2 TeV depending on the value of κ_1 . It is stronger than those from LEP II searches for anomalous four-fermion couplings [10], which are of order 400 GeV.

The NCETC models [5] do not include non-standard colored gauge bosons at all. In these models, it is the weak gauge sector which is extended to $SU(2)_h \times SU(2)_l$. Under the weak sector, third-generation fermions transform as (2,1) and light fermions as (1,2). Because the Z' boson arises from the mixing of two $SU(2)$ groups (with gauge coupling ratio $g_h/g_l \equiv \tan \phi$), the values of the coupling factors in eq. (1) are $A_{WL}^b = -\frac{1}{2}\tan \phi + \mathcal{A}$ and $A_{WL}^d = \frac{1}{2}\cot \phi + \mathcal{A}$ where \mathcal{A} is a flavor-universal term* that cancels when the difference is taken. Thus, \mathcal{R} is

$$\mathcal{R}_{NCETC} = \left[\frac{\alpha_W (\tan \phi + \cot \phi)^2}{4M_{Z'}^2} \right] \approx \frac{0.008}{\sin^2 \phi \cos^2 \phi M_{Z'}^2}. \quad (7)$$

When $\tan^2 \phi \sim 1$, the lightest allowed mass for this Z' boson will be about one-fifth that for for the topgluon of classic TC2: 620 (960) GeV if ETC does (not) contribute to ϵ . For “heavy case” NCETC, where the same condensate supplies the masses of the top quark and the electroweak bosons, this bound is far weaker than existing limit $M_{Z'} \gtrsim 1.5$ TeV from precision electroweak data [11]. For the opposite, “light case” of NCETC, the precision electroweak data [11] and LEP II compositeness searches [10] allow the Z' bosons to be as light as 400-600 GeV when $\tan^2 \phi \gtrsim 1.85$ [i.e., $\sin^2 \phi \gtrsim 0.65$], but restrict the Z' to heavier masses for smaller $\tan \phi$. Hence the limit from B-meson mixing is weaker than that from other sources for $\tan^2 \phi \lesssim 1.85$, but could be comparable or stronger for larger $\tan^2 \phi$ (especially if ETC does not contribute to ϵ). For example, if we set $\tan^2 \phi = 3$ [i.e., $\sin^2 \phi = 0.75$] in eq. (7) and scale from the results of ref. [6], the bound from FCNC is $M_{Z'} \gtrsim 650$ GeV if ETC does contribute to ϵ ($M_{Z'} \gtrsim 1$ TeV if it does not).

Having found the limits on the Z' masses in the constructive scenario, we need to discuss the extent to which that scenario applies to the flavor-universal TC2 and NCETC models. By reviewing the arguments and constraints which push flavor mixing into the D_L sector in classic TC2, we can evaluate the extent to which this is true of the other models.

In classic TC2 models, it is argued [6, 12] that both the U and the D_R matrices are nearly block-diagonal[†] (a 2x2 block for the two light generations and a 1x1 block for the third generation), forcing essentially all the quark mixing of the third generation with the other two into D_L . This texture for the U matrices essentially corresponds to having m_t arise from different physics than m_u and m_c , a condition that does obtain in both flavor-universal TC2 and NCETC models. Separately, D_R is constrained to be nearly block-diagonal in TC2 by the requirement that the b-pions formed by the strong topcolor dynamics not make

*Note that $\mathcal{A} = \sec^2 \theta_W (-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W) \cot \phi (M_W/M_{Z'})^2$ is rendered negligible by the experimental limit $M_{Z'} \gtrsim 400$ GeV and the requirement $\sin^2 \phi \leq 0.97$ [5] in order that quarks not condense.

[†]Ref. [13] discusses the alternative possibility that the U_L and D_L matrices have triangular textures, leaving the U_R and D_R matrices essentially unconstrained. The triangular textures tend to weaken or eliminate the B-meson mixing bound.

unduly large contributions to $B\bar{B}$ mixing. Kominis [14] observed that agreement of the mixing rate with experiment required

$$\frac{|D_{Lbd}^* D_{Rbb} D_{Rbd}^* D_{Lbb}|}{M_\pi^2} < 10^{-12} \text{ GeV}^{-2}. \quad (8)$$

He pointed out that this inequality would be violated by approximately two orders of magnitude if the elements of D_L and D_R were of order the square root of CKM elements (for b-pion masses of order several hundred GeV).

In the case of NCETC models, there are no topcolor dynamics and no b-pions to affect $B\bar{B}$ mixing. In flavor-universal TC2 models, the topcolor dynamics form a full set of q-pions, and a GIM mechanism prevents tree-level FCNC [4]. For contributions at one loop in flavor-universal TC2, the additional phase space suppression factor of $1/16\pi^2$ alone would suffice to satisfy eq. (8) even for $D_L \sim D_R \sim \sqrt{CKM}$. We conclude that significant inter-generational mixing in D_R is not forbidden in either flavor-universal TC2 or NCETC models.

Once mixing is allowed in the right-handed down-quark sector, the strict constraints of the constructive scenario evaporate. In eq. (2), the factor $(D_{Lbb}^* D_{Lbd})^2$ entering the contributions to ΔM_{B_d} from products of left-handed currents can take on values much larger or much smaller than $V_{tb}^* V_{td}$. Moreover, right-handed fermion currents may now also contribute to $B\bar{B}$ mixing, with a relative sign that is not universally fixed. One can see from eq. (1) that the contributions of a product of right-handed currents to $2|M_{12}|$ would replace the factor $(D_{Lbb}^* D_{Lbd})^2$ in eq. (2) by $(D_{Rbb}^* D_{Rbd})^2$; a product of a left- and a right-handed current would replace it by $(2D_{Lbb}^* D_{Lbd} D_{Rbb}^* D_{Rbd})$. At the same time, in the context of flavor-universal TC2, the hypercharge factors in $\mathcal{R}_{univ-TC2}$ (eq. (5)) would become $(Y_{1R}^b + Y_{2R}^d \tan^2 \theta_Y)^2$ for a product of right-handed currents or $(Y_{1L}^b + Y_{2L}^d \tan^2 \theta_Y)(Y_{1R}^b + Y_{2R}^d \tan^2 \theta_Y)$ for a mixed product. In NCETC models, because both $SU(2)$ groups are left-handed, the leading couplings of right-handed quarks to the Z' are flavor-universal: $A_{WR}^q = -Q_q \tan^2 \theta_W \cot \phi (M_W/M_{Z'})^2$ where Q is electric charge. Hence, if mixing in the right-handed down sector reduced the size of $(D_{Lbb}^* D_{Lbd})^2$, right-handed currents could not “pick up the slack” and produce a net NCETC contribution to B-meson mixing of the size predicted by the constructive scenario. Due to the uncertainties introduced when D_R is no longer block-diagonal, it becomes impossible to give a simple, universal size of the contribution to ΔM_{B_d} in the whole class of NCETC or flavor-universal TC2 models.

Finally, we note that the B-meson mixing limits discussed here for NCETC models also generally apply to topflavor models [15, 16, 17] which share the same extended electroweak gauge structure, but use Higgs bosons instead of technicolor to break the electroweak symmetry. Previous studies of these models have noted that large contributions to B-meson mixing are possible [19, 18] – even though electroweak data sets a lower bound of 1.7 TeV on the Z' boson [18] – but have not provided specific limits on model parameters.

To summarize: In the flavor-universal topcolor-assisted technicolor and non-commuting extended technicolor models, the constructive scenario of quark mixing, in which only left-handed quark currents contribute and they do so proportional to $(V_{tb}^*V_{td})^2$, is merely a useful benchmark, not a requirement as in classic TC2 models. Even if one assumes the constructive scenario to apply, the resulting limits on gauge boson masses from $B\bar{B}$ mixing are similar in strength to more generally applicable limits based on electroweak data. We therefore conclude that $B\bar{B}$ mixing represents a far less significant constraint on these models than on classic topcolor-assisted technicolor.

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